Adjustable Speed Drive Output Line Filters Offer Protection for Induction Motors

With the increased application of Adjustable Speed Drives (ASDs) for efficient speed control of ac motors there has been a growing number of costly drive related motor or process failures. The popular ASDs (Fig. 1) consist of a Pulse-Width Modulated (PWM) inverter switching Insulated Gate Bipolar Transistors (IGBTs) at frequencies of 2 to 20 kHz resulting in a dv/dt of 6000V/µs for power levels up to 800 kW. The high dv/dt has adverse effects on the motor insulation (due to motor terminal over-voltages) and contributes to damaging bearing currents and electromagnetic interference (EMI). In response to these concerns, a variety of mitigation techniques have emerged to address these issues. This article will review proposed ASD output line filters to reduce motor terminal over-voltages and the resulting winding stresses.

Motor Terminal Over-Voltages

In many new and retrofit industrial applications the PWM inverter and motor must be at separate locations, thus requiring long motor leads. The long cable employed between the inverter and the motor contributes to a damped high frequency ringing at the motor terminals resulting in excessive over-voltages which stress the motor insulation. Also, the motor impedance, which is dominated by the winding inductance, presents an effective

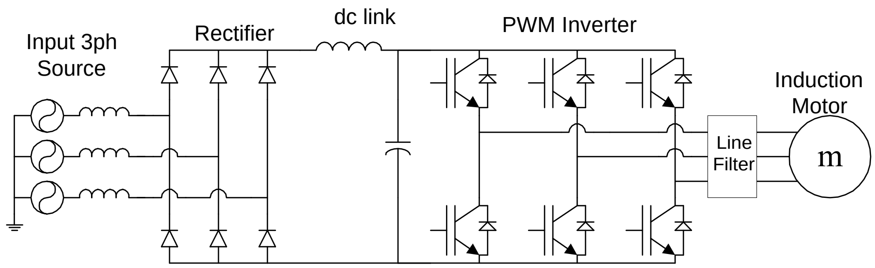

Fig. 1 A PWM inverter-based ASD controlling an induction motor.

open circuit at high frequencies at the end of the long cable. This produces a reflected voltage at the end of the cable approximately equal in magnitude and with the same sign, resulting in twice the magnitude of the incident voltage at the motor terminals as shown in Fig. 2. The peak motor terminal voltage is a function of the cable length, the load reflection coefficient (Γ_L: typically 0.9 for motors less than 25 hp), the inverter output pulse rise time and the pulse velocity which is typically half the speed of light, or 150 m/µs. In general, the longer the cable length and the higher the dv/dt (or lower the rise time) the higher the over-voltage as indicated in Table 1 and Fig. 3.

The over-voltage at the motor terminals causes winding dielectric insulation stresses that are most pronounced at the turn insulation adjacent to the coil terminals. Low voltage (230/460V) induction motors powered by PWM inverters are predominantly mush (or random) wound. Thus, in the coil-insertion winding process, the first and last turn within a coil have a chance to cross over or lie adjacent to each other in the stator slot, and this is the point where the insulation is stressed the most. While NEMA Standard MG1, Part 31 specifies that stator winding insulation systems for definite purpose inverter-fed motors should be designed to operate under $V_{peak} \leq 1600V$, motor manufacturers report that at typical IGBT rise times of 0.1µs, voltages ≥ 1000V can exceed the dielectric withstand capability of standard motors resulting in failures.

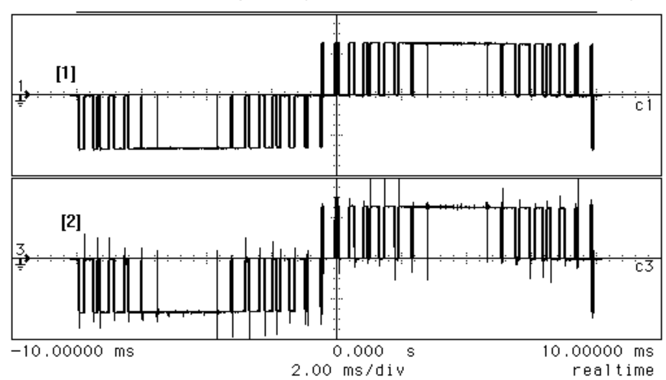

Fig. 2 PWM inverter output voltage [1] and motor terminal voltage [2], for a 5kVA drive, 2kHz switching freq., 60Hz operating freq. and 50ft of cable.

Table I. Minimum cable length and PWM rise time after which voltage doubling occurs at the motor terminals for motors < 25hp.

PWM pulse rise time	Minimum cable length
0.1 μs	19 ft
0.5 μs	97 ft
1.0 μs	195 ft
2.0 μs	390 ft
3.0 μs	585 ft
4.0 μs	780 ft
5.0 μs	975 ft

Motor Terminal Filter

Due to the dominating winding inductance, the characteristic impedance of smaller motors (<25hp) can be ten to one-hundred times that of the characteristic impedance of the cable connecting the drive to the motor. Therefore, the incident wave voltage will be reflected back towards the inverter and the voltage amplitude at the terminals of the motor will approximately double. However, if the cable is terminated with the cable surge impedance, the incident voltage will not be reflected and significant over voltages at the terminals of the motor can be prevented. It should be noted that for larger motors (>50hp) the motor impedance significantly decreases (decreasing the impedance mismatch at the motor terminals) and the voltage reflection phenomena may not be as pronounced.

A first-order filter consisting of a capacitor in series with a resistor can be designed, and optimized for minimum losses, to match the surge impedance of the cable and minimize the motor terminal over-voltage. Fig. 4 illustrates the effectiveness of a motor terminal impedance matching filter.

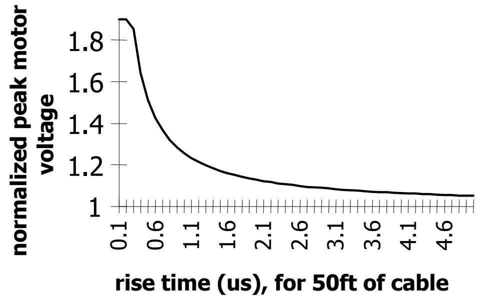

Fig. 3 Normalized motor voltage vs. rise time due to reflections.

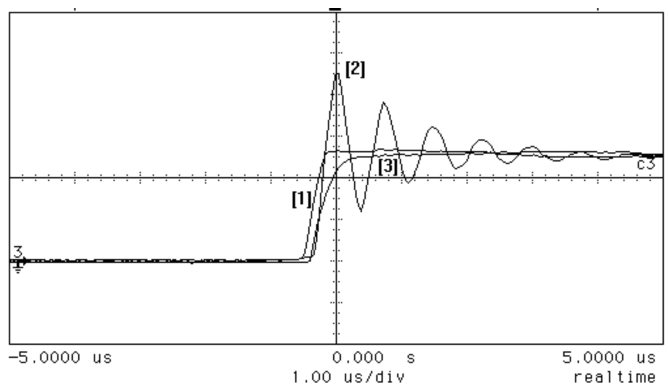

Fig. 4 5 hp, 460V, Leading edge voltages of inverter output [1] motor terminal without filter [2], motor terminal with impedance matching filter [3].

Inverter Output Filter

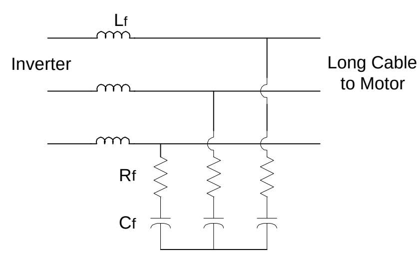

Fig. 5 Inverter output low pass filter.

In many applications the motor terminals may not be accessible, as with submersible pumps. Fig. 3 shows that increasing the rise time of the PWM inverter output voltage applied to the cable above a critical value will significantly reduce over-voltages due to reflections. Thus a low pass filter as shown in Fig. 5, placed at the output terminals of the inverter can be specially designed to decrease the inverter output pulse dv/dt and thereby reduce the over-voltage and ringing at the motor terminals. From the motor terminal voltage equations, and Fig. 3, the critical rise times for a given cable length can be approximated, i.e. 1.5μs for 50ft of cable, 2.5μs for 100ft and 3.5μs for 200ft. By using the exponential equations of the rising and falling edges of the PWM inverter output waveform passed through the low pass filter of Fig. 5, the filter component values necessary to reduce the dv/dt can be expressed in terms of the critical rise time. Fig. 6 illustrates the effectiveness of a low pass inverter output filter.

Inverter Output Series Reactor

A series reactance of sufficient size (5%) acts as a current-limiting device and filters the PWM waveform, slowing down the dv/dt and attenuating electrical noise. These reactors also protect the controller from either a short circuit in the load or a surge in the output current by limiting the short circuit current. However, this method can affect the transient performance of the drive and the reactor is fairly large. Figs. 7 and 8 show the resulting waveforms with the application of the 5% series reactor on a 5kVA drive system. Note the near sinusoidal nature of the motor terminal voltage with the series reactor as compared to Fig. 2.

Filter Comparisons

All three line filters reviewed effectively reduce the motor terminal over-voltage to below critical dielectric withstand capabilities of standard motors. Table II. gives a breakdown of the three filters.

Table II. Filter Comparisons

Motor Terminal Filter
Connected in shunt at motor term.
Des. to match char. imp. of cable
Not dep. on the cable length
Losses are more or less fixed
Size/Cost more or less fixed/smallest
Inverter Output Filter
Connected in series to inv. o/p term.
Designed to reduce the dv/dt below a critical value
Dep. on the cable length
Losses are dep. on motor kVA
Size/Cost dep. on motor kVA
Series Reactor
Connected in series to inv. o/p term.
Acts as current limiting device and reduces dv/dt
Dep. on size of system
Losses are dep. on motor kVA
Size/Cost dep. on motor kVA/largest

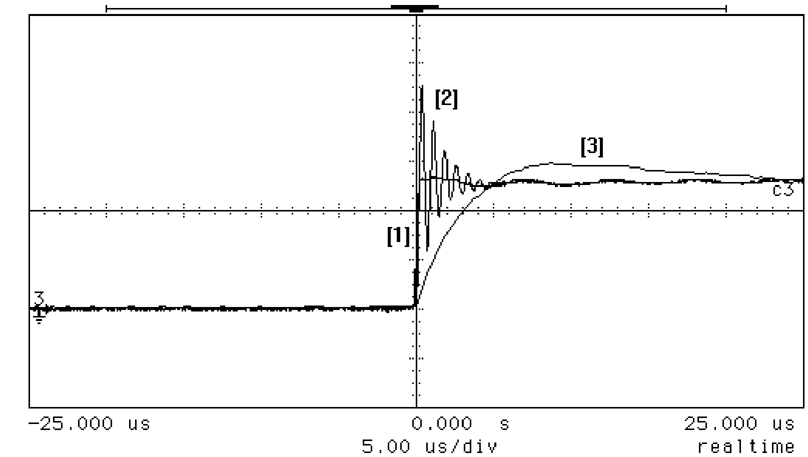

Fig. 6 5 hp, 460V, Leading edge voltages of inverter output [1], motor terminal without filter [2], motor terminal with inverter output RLC filter [3].

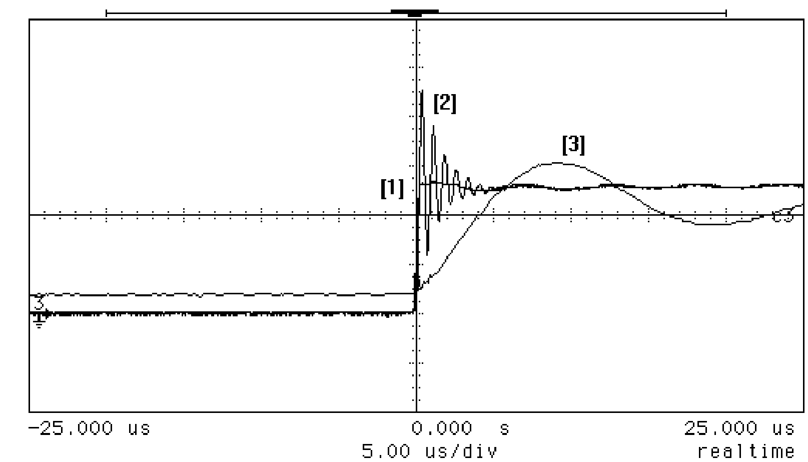

Fig. 7 5hp, 460V, Leading edge voltages of inverter output [1], motor terminal without filter [2], motor terminal with 5% series reactor [3].

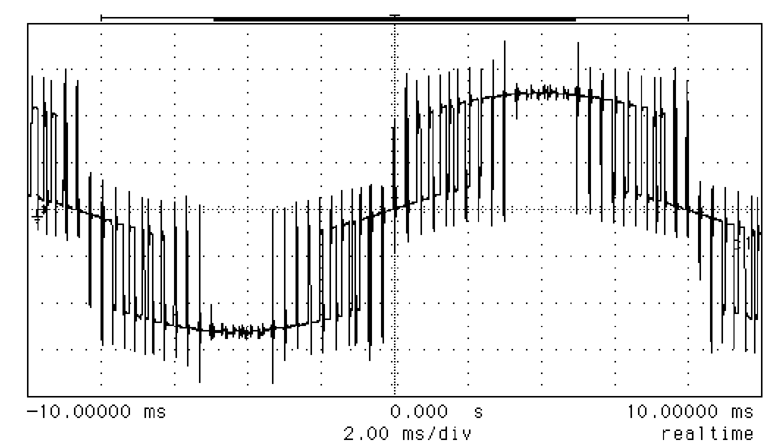

Fig. 8 5hp, 460V, Expanded motor terminal voltage with 5% series reactor.